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Gamble et al.

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[54] **COOLING SYSTEM FOR SUPERCONDUCTING MAGNET**

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[73] Assignee: **American Superconductor Corporation**, Westborough, Mass.

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[51] **Int. Cl.**[6] **F17C 3/10**; F25B 19/00

[52] **U.S. Cl.** **62/48.2**; 62/51.1

[58] **Field of Search** 62/48.2, 51.1

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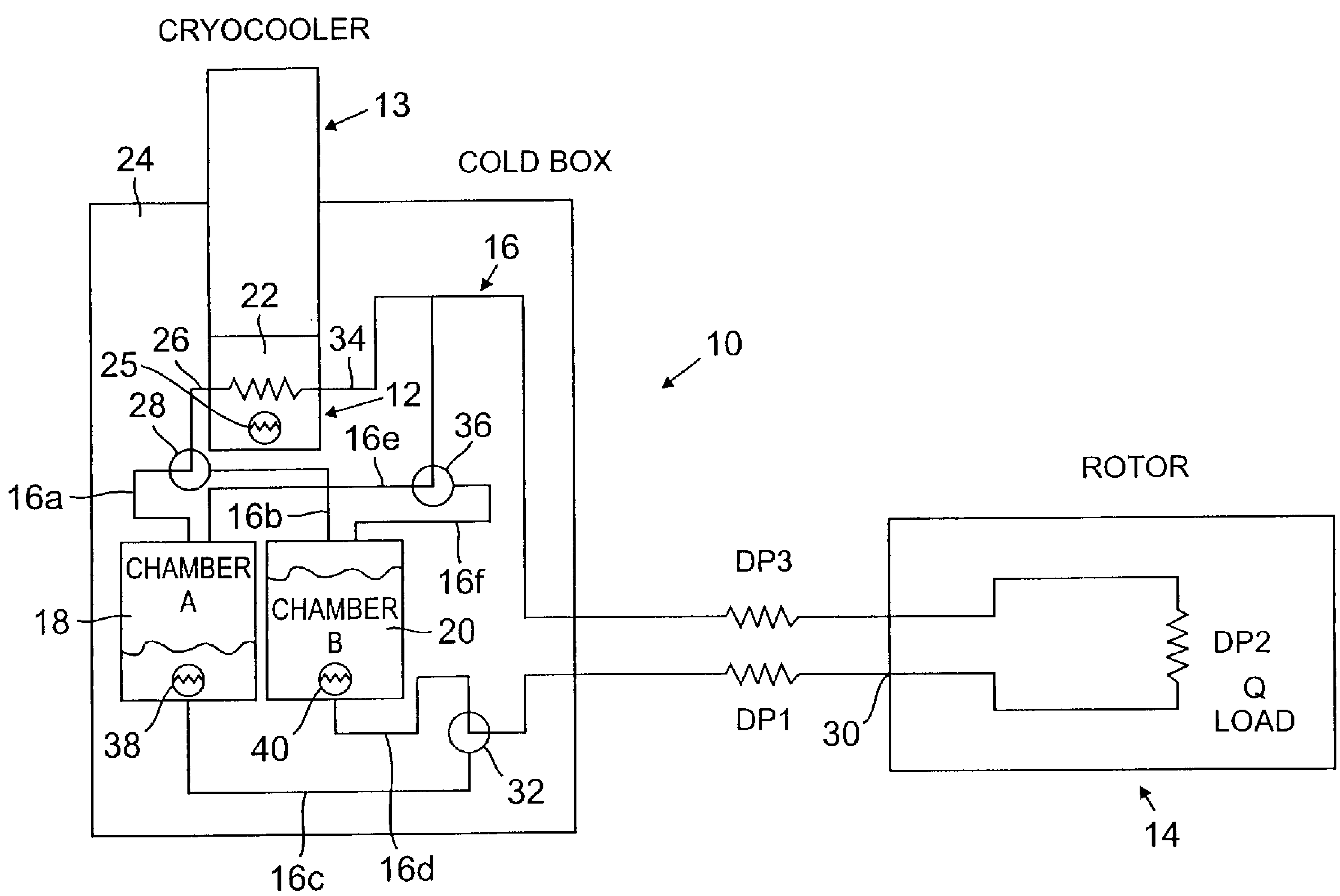
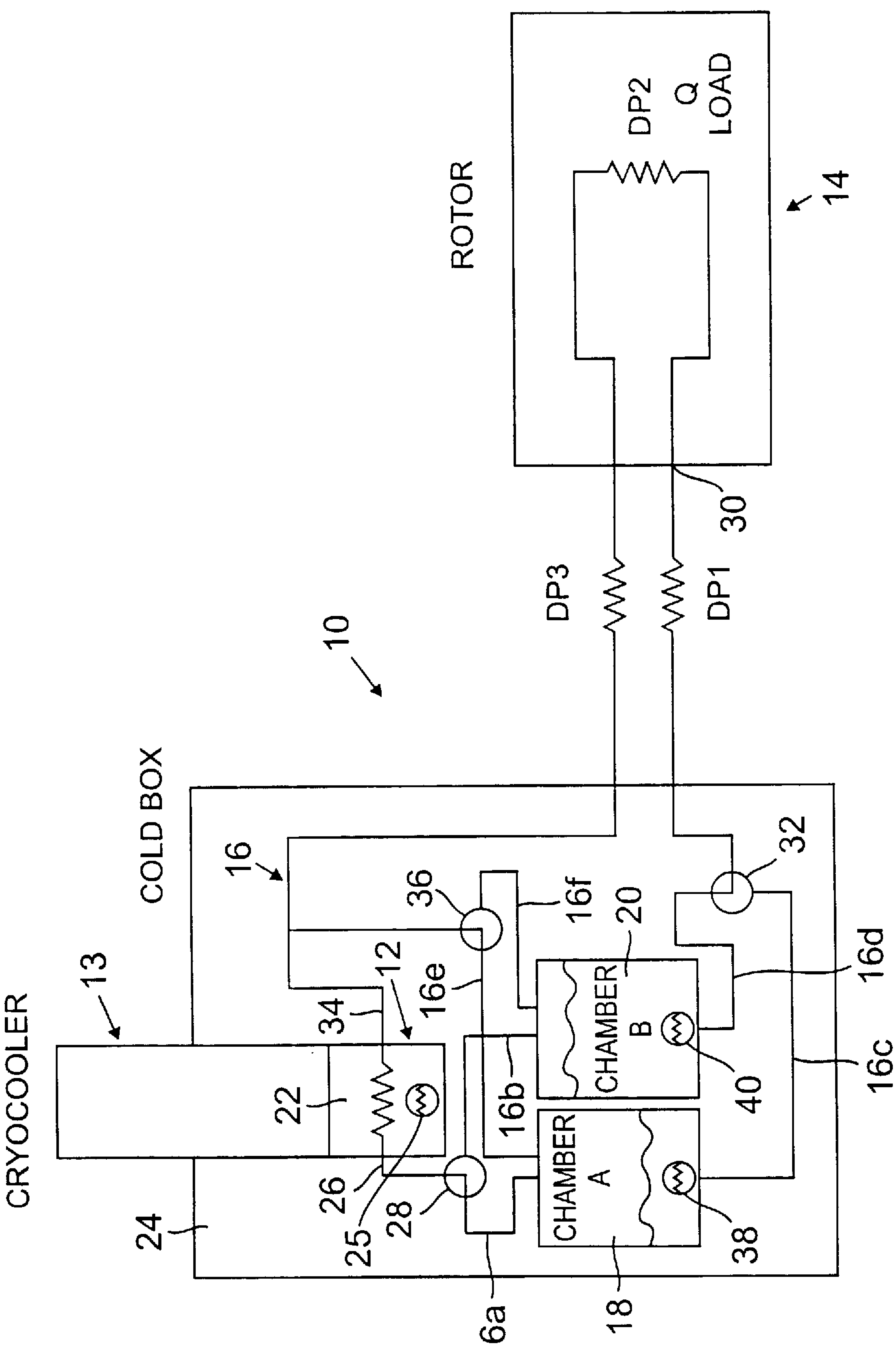
[57] **ABSTRACT**

A cooling system is configured to control the flow of a refrigerant by controlling the rate at which the refrigerant is heated, thereby providing an efficient and reliable approach to cooling a load (e.g., magnets, rotors). The cooling system includes a conduit circuit connected to the load and within which a refrigerant circulates; a heat exchanger, connected within the conduit circuit and disposed remotely from the load; a first and a second reservoir, each connected within the conduit, each holding at least a portion of the refrigerant; a heater configured to independently heat the first and second reservoirs. In a first mode, the heater heats the first reservoir, thereby causing the refrigerant to flow from the first reservoir through the load and heat exchanger, via the conduit circuit and into the second reservoir. In a second mode, the heater heats the second reservoir to cause the refrigerant to flow from the second reservoir through the load and heat exchanger via the conduit circuit and into the first reservoir.

20 Claims, 3 Drawing Sheets

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COLD BOX
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CHAMBER A
CHAMBER B

FIG. 1

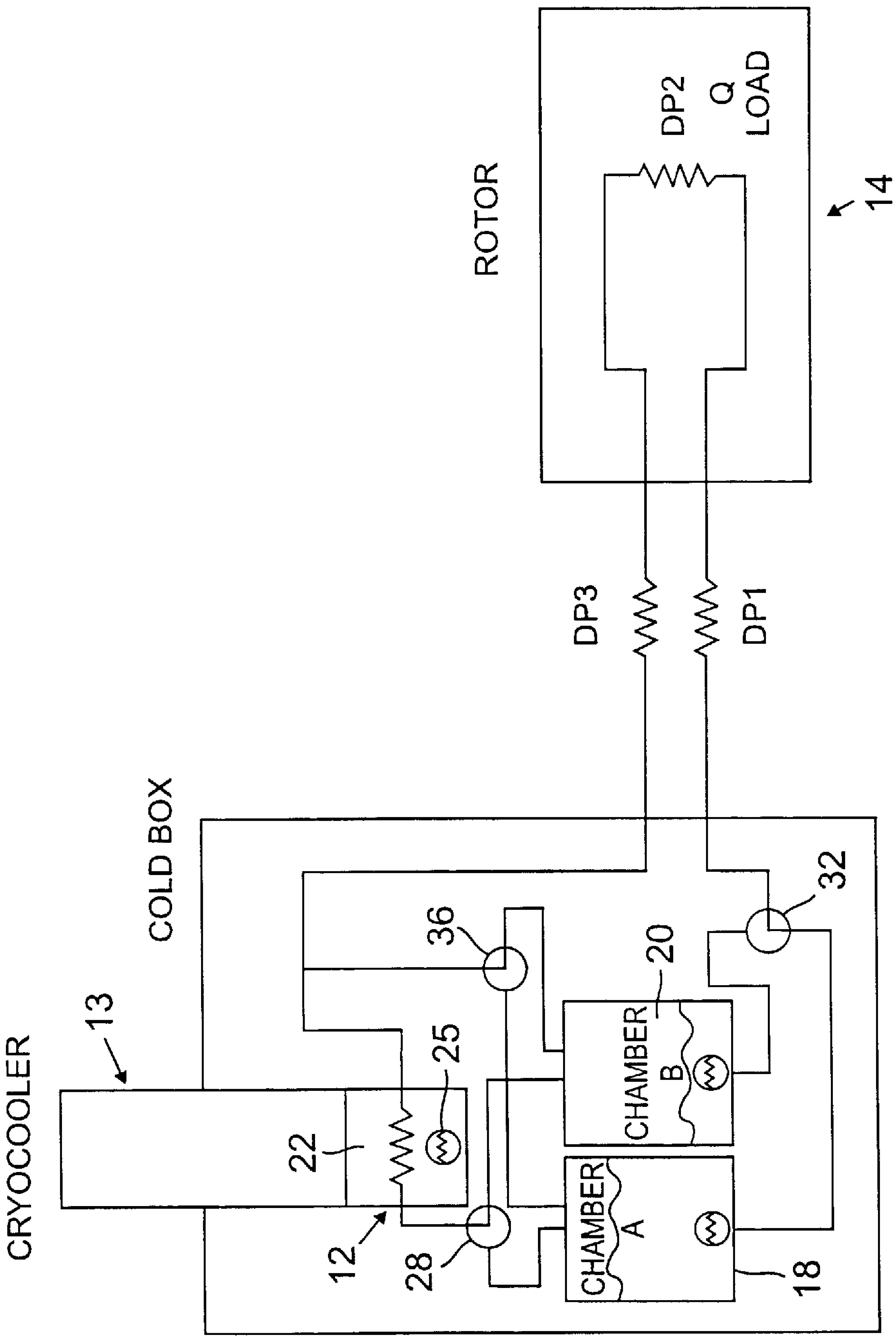
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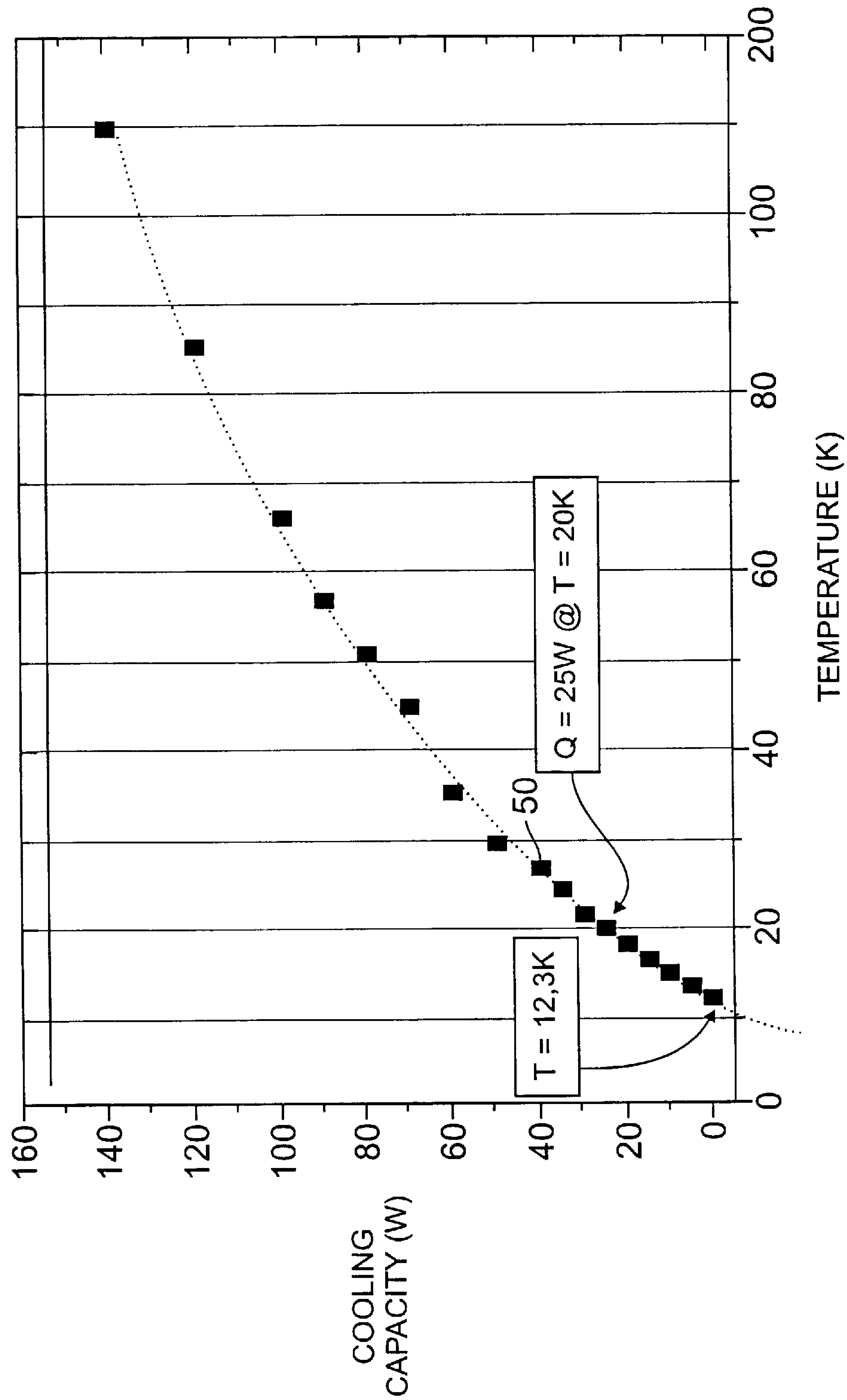
FIG. 2



COOLING CAPACITY (W)
160
140
120
100
80
60
40
20
0
TEMPERATURE (K)
0
20
40
60
80
100
200
Q = 25W @ T = 20K
T = 12,3K
50

FIG. 3

COOLING SYSTEM FOR SUPERCONDUCTING MAGNET

This invention arose in part out of research pursuant to Subcontract No. QZ001 awarded by the Department of Energy under Prime Contract No. DE-FC36-93CH10580.

BACKGROUND OF THE INVENTION

The invention relates to cooling loads including superconducting components.

Superconducting rotating machines such as motors and generators must be cooled such that the field structures of their rotors are in the superconducting state. The conventional approach to cooling rotor field coils is to immerse the rotor in a cryogenic liquid. For example, a rotor employing field coils made of high temperature superconducting materials might be immersed in liquid nitrogen. In this case, heat generated by or conducted into the rotor is absorbed by the cryogenic liquid which undergoes a phase change to the gaseous state. Consequently, the cryogenic liquid must be replenished on a continuing basis.

Another approach for cooling superconducting components is the use of a cryogenic refrigerator or cryocooler. Cryocoolers are mechanical devices operating in one of several thermodynamic cycles such as the Gifford-McMahon cycle and the Stirling cycle. Cryocoolers have found application, for example, in cooling the stationary magnets in magnetic resonance imaging systems. See, for example, M. T. G van der Laan et al., "A 12K superconducting Magnet System, Cooled via Thermal Conduction by Means of Cryocoolers", *Advances in Cryogenic Engineering*, Volume 37, Part B, (Proceedings of the **1991** Cryogenic Engineering Conference) edited by R. I/V. Fast, page 1517 and G. Walker et al., "Cryocoolers for the New High-Temperature Superconductors," *Journal of Superconductivity*, Vol. 1No.2, 1988. Good cryocooler performance depends in large part on a design optimized for the actual conditions within which the cryocooler operates. More recently cryocoolers have been adapted for operation with rotors, such as superconducting motors and generators. One approach for doing so is described in U.S. Pat. No. 5,482,919, entitled "Superconducting Rotor", issued to Joshi, assigned to the assignee of the present invention, and incorporated herein by reference.

SUMMARY OF THE INVENTION

The invention features a cooling system configured to control the flow of a refrigerant through a load, such as a superconducting magnet or rotor, by controlling the rate at which the refrigerant is heated, thereby providing an efficient and reliable approach to cooling the load. The cooling system delivers the refrigerant to the load through a heat exchanger which is connected to a cryocooler coldhead.

In a general aspect of the invention, the cooling system includes a conduit circuit connected to the load and within which a refrigerant circulates; a first and a second reservoir, each connected within the conduit, each holding at least a portion of the refrigerant; and a heater configured to independently heat the first and second reservoirs. In a first mode, the heater heats the first reservoir, thereby causing the refrigerant to flow from the first reservoir through the load and heat exchanger via the conduit circuit and into the second reservoir. In a second mode, the heater heats the second reservoir to cause the refrigerant to flow from the second reservoir through the load and heat exchanger via the conduit circuit and into the first reservoir.

In general, among many of its advantages, the cooling system provides a relatively simple and economic approach for circulating a refrigerant used to cool the load. In particular, the cooling system does not require a pump or compressor to circulate the refrigerant through the load. Eliminating the need for such a pump or compressor is advantageous because compressors generally do not operate reliably or efficiently at cryogenic temperatures. Indeed, in many conventional superconducting cooling systems, the compressor used to circulate the refrigerant through the load is required to be operated, with added expense, at room temperature. In others, an expensive and potentially unreliable cryogenic compressor is used to circulate the flow.

The cooling system is particularly advantageous for cooling superconducting loads in applications where it is a problem locating the cold head where the refrigeration is required. For example, in magnetic resonance imaging applications, the cold head is generally located remotely from the magnet so as not to interfere with the magnetic homogeneity of the magnet. Another application involves cooling a load which is in a rotating reference frame, such as a superconducting rotor in a motor. Although rotating, leak-tight non-contaminating high pressure seals have been used in these applications, the seals are expensive and require frequent maintenance. Moreover, in certain applications, secondary flows created by high centrifugal flows preclude rotating the cold head.

Embodiments of the invention may include one or more of the following features.

The cooling system includes valves which are connected within the conduit circuit for controlling the flow into and out of the reservoirs. For example, a first valve has an input coupled to the first and the second reservoirs (e.g., at their bottom ends) and an output coupled to the load. Actuating the first valve controls the source of refrigerant to the load. A second valve has an input coupled to an output of the heat exchanger and the first reservoir (e.g., at its top end). Actuating the second valve controls which of the reservoirs receives the recondensed refrigerant from the heat exchanger. A third valve has an input coupled to an input of the heat exchanger and the first and second reservoirs (e.g., at their top ends). Actuating the third valve controls which of the reservoirs is connected to a venting backup line that connects the reservoirs to the input of the condensing heat exchanger.

The heater includes a pair of heating elements, each heating element associated with a respective one of the first and second reservoirs. The cooling system includes a cold box which encloses the heat exchanger and the first and the second reservoirs. The conduit circuit is formed of vacuum insulated transfer lines.

The refrigerant used in the cooling system is selected from a group consisting of helium, neon, nitrogen, hydrogen, oxygen or mixtures thereof. Neon is an attractive choice because it has a phase transition temperature at 27° K (one atmosphere), a temperature well-suited for cryogenically cooling loads formed of high temperature superconductors.

However, the invention is equally applicable for cooling components at cryogenic temperatures higher than those required for both high and low temperature superconductors. At those cryogenic temperatures (e.g., 150°–170° K), a fluorocarbon such as a fluoroalkane may be used. The fluoroalkane may be anyone of octafluoropropane (perfluoropropane), decafluro n-butane (perfluoro n-butane), decafluoro isobutane (perfluoro isobutane), fluoroethane

(e.g., between its boiling and melting points), hexafluoropropane, heptafluoropropane (e.g., 1,1,1,2,3,3,3-heptafluoropropane and 1,1,1,2,2,3,3-heptafluoropropane) and isomers and mixtures thereof.

In another aspect of the invention, the above described cooling system is used to cool a load. The method of cooling includes heating the first reservoir to cause the refrigerant to flow from the first reservoir through the load and heat exchanger via the conduit circuit and into the second reservoir, heating of the first reservoir continuing until the refrigerant is substantially depleted from the first reservoir. The second reservoir is then heated to cause the refrigerant to flow from the second reservoir through the load and heat exchanger via the conduit circuit and into the first reservoir, heating of the second reservoir continuing until the refrigerant is substantially depleted from the second reservoir.

In one embodiment, the steps of heating the first and second reservoirs are repeated in alternating manner. The method of cooling the load can be performed at a pressure level substantially equal to one atmosphere. Alternatively, the temperature of the cooling system can be changed by operating the system at a pressure level greater than one atmosphere.

Other features and advantages will become apparent from the following description and from the claims.

BRIEF DESCRIPTION OF THE DRAWING

FIG. **1** is a schematic representation of a cooling system in a first mode of operation according to the invention.

FIG. **2** is a schematic representation of the cooling system of FIG. **1** in a second mode of operation.

FIG. **3** is a graph indicating the cooling performance of an exemplary cryocooler used in the cooling system of FIG. **1**.

DESCRIPTION

Referring to FIGS. **1** and **2**, a cooling system **10** includes a heat exchanger **12** connected to a load **14** (e.g., a rotor of a superconducting motor) via a conduit circuit **15** through which neon refrigerant flows. The conduit circuit is formed of vacuum insulated lines **16** and represents a secondary cooling circuit (or loop) used to provide cooling from a cryocooler **13**.

Heat exchanger **12** may be in the form of any of a wide variety of configurations including perforated plate or coiled tube heat exchangers. Heat exchanger **12** is directly attached (e.g., by solder or bolting) to cryocooler **13** which is generally considered to be a part of the primary cooling circuit. Cryocooler **13** may be any of a wide variety cryocooling refrigerators designed to operate according to one of several thermodynamic cycles including Gifford-McMahon, Stirling and pulse-tube cycle, such as those described in U.S. Pat. No. 5,482,919. One example of a cryocooler appropriate for use in cooling system **10** is Model No. RGS 120-T, manufactured by Leybold, Inc., Cologne, Germany. Cryocooler **13** includes a heater **25** which, in conjunction with a temperature sensor (not shown) and feedback loop arrangement, prevents the neon refrigerant from freezing. Referring to FIG. **3**, the amount of cooling power in units of watts as a function of temperature in °K is shown. This performance curve indicates that cryocooler **13** is capable of producing greater than 40 watts of cooling power at 27° K (point **50**) which, for reasons discussed below, is the temperature most appropriate for cooling with a neon refrigerant a load formed of high temperature superconductor (HTS).

Cooling system **10** also includes a pair of reservoirs (e.g., storage chambers) **18**, **20**, each connected to heat exchanger

12 which is attached to the cold head end **22** of cryocooler **13**. Reservoirs **18**, **20** and cold head end **22** are enclosed within a cold box **24** having a blanket of thermal insulation or a vacuum shield (not shown) surrounding the components.

A pair of heaters **38**, **40** (e.g., nichrome wire heaters) are positioned to apply heat to respective, bottom ends of reservoirs **18**, **20**. Reservoirs **18**, **20** are each connected, at their top ends, to an output **26** of cold head end **22** through an input valve **28** via lines **16***a*, **16***b*, respectively. The bottom ends of reservoirs **18**, **20** are connected to an input **30** of load **14** through an output valve **32**, via lines **16***c*, **16***d*, respectively.

Reservoirs **18**, **20** are also connected, at their top ends, to an input **34** of heat exchanger **12** through a venting valve **36** via lines **16***e*, **16***f*, respectively. As will be discussed below, lines **16***e*, **16***f* provide venting paths which ensure a constant and steady flow of the neon refrigerant from output **26** of cold head **22** into the reservoirs.

Valves **28**, **32**, **36** may be any of a wide variety of valves capable of operating at cryogenic temperatures including control or solenoidal valves. Valcor Scientific, Inc., Springfield, N.J. provides valves (e.g., on/off type) which are appropriate for use as valve **28**, **32** or **36** in cooling system **10**.

Referring to FIG. **1**, in operation, cooling system **10** is shown in a first mode of operation with valve **28** actuated to connect output **26** of heat exchanger **12** to the input of reservoir **18** rather than to reservoir **20**. Valve **32** is actuated so that load **14** receives flow of neon refrigerant from the output of reservoir **20** rather than reservoir **18**. In other words, valves **28**, **32** are actuated so that reservoir **20** serves as a neon refrigerant source to load **14** and reservoir **18** serves as a depository for the re-condensed refrigerant returned from load **14**. Valve **36** is also actuated to connect reservoir **18** to input **34** of heat exchanger **12** and disconnect reservoir **20** from the cryocooler.

Heater **40** is then activated to apply a small amount of heat to reservoir **20** causing a relatively small amount of the liquid neon refrigerant in reservoir **20** to boil. The phase change increases the pressure in reservoir **20**, thereby generating a force which causes the neon refrigerant in a liquid state to flow to load **14**. The liquid neon refrigerant flows through load **14** where it undergoes a phase transition to the vapor state before travelling to input **34** of heat exchanger **12**. The vapor neon refrigerant is recondensed into its liquid state at heat exchanger **12** and is passed into reservoir **18** through valve **28**. When the neon refrigerant in reservoir **20** is substantially depleted, heater **40** is shut off ending the first mode of operation.

Referring to FIG. **2**, in the second mode of operation, valves **28**, **32**, and **36** are actuated so that reservoir **18** (which was filled during the first mode of operation) serves as the neon refrigerant source to load **14** and reservoir **20** (which was emptied during the first mode of operation) serves as the depository for the re-condensed refrigerant returned from load **14**. Valve **36** is also actuated to connect reservoir **20** to input **34** of heat exchanger **12** and disconnect reservoir **18** from the heat exchanger.

In the second mode of operation, heater **40** (associated with reservoir **20**) is turned off and heater **38** (associated with reservoir **18**) is activated to cause a small amount of neon refrigerant in reservoir **18** to boil, thereby causing the liquid neon refrigerant to flow through load **14**. When the neon refrigerant in reservoir **18** is substantially depleted, heater **38** is shut off ending the second mode of operation and the cycle is repeated.

Other embodiments are within the scope of the claims. For example, although neon was used as the refrigerant in the above description of cooling system **10**, other working fluids, such as helium, nitrogen, oxygen and mixtures thereof may be used depending upon the particular application, temperature of operation, and the desired level of cooling.

Neon, however, is particularly advantageous for cooling system **10** because it has a phase change from liquid to gas occurring at 27° K (one atmosphere) which is a temperature well suited for cooling superconducting components (e.g., magnets, rotors) fabricated from HTS materials, such as those described in U.S. Pat. No. 5,581,220, issued to Rodenbush et al., assigned to the assignee of the present invention and incorporated herein by reference. Thus, neon can be used to provide constant temperature refrigeration at 27° K.

Another reason why neon is well-suited as a refrigerant in cooling system **10** relates to the ratio of its density as a liquid and density as a vapor. Referring to K. D. Timmerhaus et al., Cryogenic Process Engineering, Plenum Press (1989), the densities of neon at 27° K (at one atmosphere) for liquid and gas is 1206 and 9.367 kg/m^3, respectively, the ratio being 130. Thus, boiling 1 cm^3 of liquid neon creates 130 cm^3 of equivalent vapor. Put another way, only 1 cm^3 is boiled out of 130 cm^3 to provide a displacing function.

The concept of the invention is equally applicable for cooling components at temperatures higher than those required for both high and low temperature superconductors. For example, cooling system **10** can also be used to cool cryogenic electronic systems at temperatures between 90° and 236° K (preferably, 150°–170° K). Examples of cryogenic electronic systems are described in U.S. Pat. No. 5,612,615, issued to Gold et al., assigned to the assignee of the present invention and incorporated herein by reference. In such cryogenic applications, refrigerants other than those described above may be preferable. For example, a fluoroalkane, or other fluorocarbon may be used, such as those described in co-pending application U.S. Ser. No. 08/698,806, entitled "Methods And Apparatus For Cooling Systems For Cryogenic Power Conversion Electronics", assigned to the assignee of the present invention and incorporated by reference.

In high voltage applications, the refrigerant used for providing refrigeration is desired to have a high dielectric strength characteristic. The above described fluoroalkanes, for example, are known to have such a characteristic.

In the above embodiment, cooling system **10** was operated at a pressure of one atmosphere; thus, providing a 27° K refrigerator. However, in certain applications, it may be desirable to operate at a different pressure, thereby changing the temperature of the cooling system. For example, the operating pressure of the system could be increased to provide a 30° K cooling system.

What is claimed is:

1. A cooling system for circulating a refrigerant flowing through a heat exchanger which is connected to a cryocooler coldhead, the cooling system delivering the refrigerant to a load and comprising:

a conduit circuit connected to the load and within which the refrigerant circulates;

a first and a second reservoir, each connected within the conduit, each holding at least a portion of the refrigerant;

a heater configured to independently heat the first and second reservoirs, the heater operating, in a first mode, to heat the first reservoir, thereby causing the refrigerant to flow from the first reservoir through the load and heat exchanger via the conduit circuit and into the second reservoir, and operating, in a second mode, to heat the second reservoir to cause the refrigerant to flow from the second reservoir through the load and heat exchanger via the conduit circuit and into the first reservoir.

2. The system of claim **1** further comprising a first valve connected within the conduit circuit, the first valve having an input coupled to the first and the second reservoirs and an output coupled to the load.

3. The system of claim **2** further comprising a second valve connected within the conduit circuit, the second valve having an input coupled to an output of the heat exchanger and first reservoir.

4. The system of claim **3** further comprising a third valve connected within the conduit circuit, the third valve having an input coupled to an input of the heat exchanger and the first and second reservoirs, and the conduit circuit includes a venting backup line coupled between the heat exchanger, the third valve and the first and second reservoirs.

5. The system of claim **1** wherein the heater comprises a pair of heating elements, each heating element associated with a respective one of the first and second reservoirs.

6. The system of claim **1** further comprising a cold box which encloses the heat exchanger and the first and the second reservoirs.

7. The system of claim **1** wherein the conduit circuit includes vacuum insulated transfer lines.

8. The system of claim **1** wherein the load is a rotor of a superconducting motor.

9. The system of claim **1** wherein the refrigerant is selected from a group consisting of helium, neon, nitrogen, hydrogen, oxygen and mixtures thereof.

10. The system of claim **8** wherein the refrigerant is neon.

11. The system of claim **1** wherein the refrigerant is a fluorocarbon liquid cryogen.

12. The system of claim **11** wherein the liquid cryogen is a fluoroalkane.

13. A method of cooling a load with a system having a heat exchanger coupled to a cryocooler coldhead and the load via a conduit circuit having a refrigerant circulating therethrough, the method comprising:

a) providing a first and a second reservoir, each connected within the conduit, each holding at least a portion of the refrigerant;

b) heating the first reservoir to cause the refrigerant to flow from the first reservoir through the load and heat exchanger via the conduit circuit and into the second reservoir, said heating of the first reservoir continuing until the refrigerant is substantially depleted from the first reservoir; and

c) heating the second reservoir to cause the refrigerant to flow from the second reservoir through the load and heat exchanger via the conduit circuit and into the first reservoir, said heating of the second reservoir continuing until the refrigerant is substantially depleted from the second reservoir.

14. The method of claim **13** further comprising repeating steps b) and c) in alternating manner.

15. The method of claim **13** wherein the system further comprises a first valve and a second valve connected within the conduit circuit, the first valve having an input coupled to the first and the second reservoirs and an output coupled to the load, the second valve having an input coupled to an output of the heat exchanger and first reservoir, the method further comprising:

prior to step b), actuating the first valve to allow the refrigerant to flow from the first reservoir to the load and actuating the second valve to allow the refrigerant to flow into the second reservoir from the load; and

prior to step c), actuating the first valve to allow the refrigerant to flow from the second reservoir to the load and actuating the second valve to allow the refrigerant to flow into the first reservoir from the load.

16. The method of claim **15** wherein the system further comprises a third valve connected within the conduit circuit, the third valve having an input coupled to an input of the heat exchanger and the first and second reservoirs, and the conduit circuit includes a venting backup line coupled between the third valve and the first reservoir and second reservoirs, the method comprising:

prior to step b), actuating the third valve to allow the refrigerant to flow from the first reservoir to the load; and

prior to step c), actuating the third valve to allow the refrigerant to flow from the second reservoir to the load.

17. The method of claim **13** wherein the refrigerant is selected from a group consisting of helium, neon, nitrogen, hydrogen, oxygen, a fluorocarbon and mixtures thereof.

18. The method of claim **13** further comprising performing steps a), b) and c) at a pressure level substantially equal to one atmosphere.

19. The method of claim **13** further comprising performing steps a), b) and c) at a pressure level exceeding one atmosphere.

20. A system for cooling a load to cryogenic temperatures comprising:

a conduit circuit, connected to the superconducting load and within which a refrigerant circulates;

a heat exchanger, connected within the conduit circuit and to a cryocooler coldhead, the heat exchanger disposed remotely from the load;

a first and a second reservoir, each connected within the conduit, each holding at least a portion of the refrigerant;

a heater configured to independently heat the first and second reservoirs, the heater operating, in a first mode, to heat the first reservoir, thereby causing the refrigerant to flow from the first reservoir through the superconducting load and heat exchanger via the conduit circuit and into the second reservoir, and operating, in a second mode, to heat the second reservoir to cause the refrigerant to flow from the second reservoir through the superconducting load and heat exchanger via the conduit circuit and into the first reservoir.

* * * * *